Modal MAC Analysis vs. Sine Vibe
A Case Study

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Overview

Sine Vibe vs. Modal Mass Acceleration Analysis

- Describe Modal Mass Acceleration Curve (MMA Curve): the core concept of MMA Load Analysis methodology, widely adopted at JPL
- Introduce *the notion* of mapping modal acceleration responses to the space of acceleration vs. effective mass and compare with MMA Curve
- Evaluate the responses of different enforced acceleration sine vibration notching strategies with MMA Curve
- Provide connection between sine vibe analysis with MMA Load analysis methodology

Modal MAC Loads Analysis - Background (1/3)

- **Bounding Loads** – Methodology generates bounding loads for the low frequency launch dynamic environments (< 100 Hz) for structural design
  - *Not a simulation, but bound loads from a CLA*
- **Quick Turnaround** – Loads analysis for a payload (e.g. spacecraft) accomplished in 1 – 2 weeks, as opposed to the typical 2 - 3 month turnaround time for a coupled loads cycle
  - *Modal MAC Analysis 1 – 2 Weeks*
  - *Coupled Loads Analysis 2 – 3 Months*
- **Accommodates Large Output Requests** – Possible to output loads for an entire payload model
  - *Modal MAC Analysis > 500,000 Output Items*
  - *Coupled Loads Analysis < 10,000 Output Items*

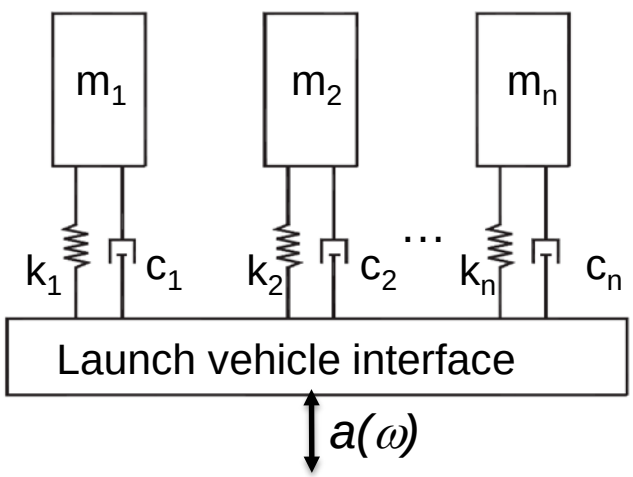
Modal MAC Loads Analysis - Background (2/3)

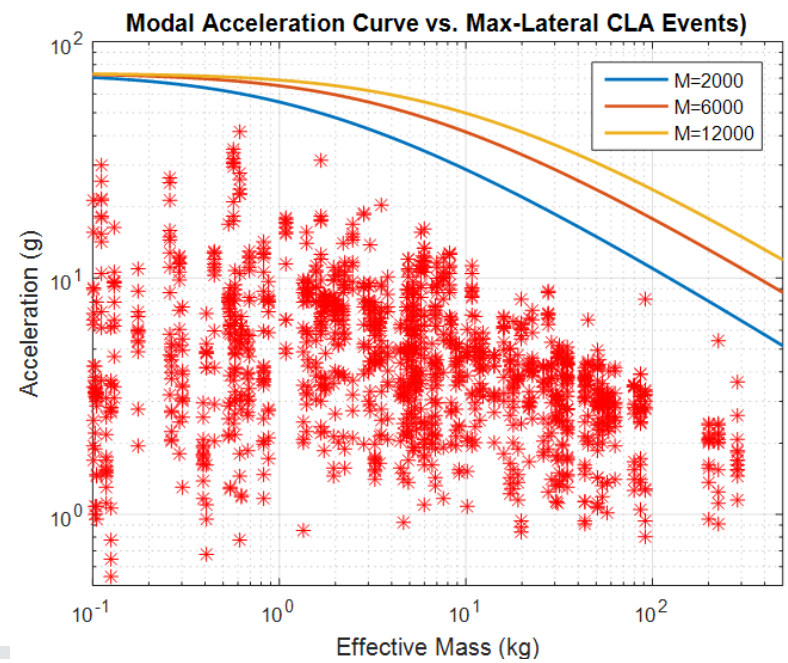
Modal Mass Acceleration Curve (MMA Curve)

- MMA-Curve based on widely accepted principle: acceleration response of a base driven system is inversely proportional to the square root of its mass.
- Each mode characterized by its *effective mass* of a spring-mass system cantilevered from the payload to launch vehicle interface
- The curve is intended to bound the CLA
  - *Parameters tuned to bound CLA events*

$$MMAC(m) = \frac{Go}{\sqrt{\frac{m}{M} + \left(\xi_{sc} + \xi_{lv}\right)^2}} e^{\frac{-\alpha}{\tan(\alpha)}}$$

$$\alpha = Tan^{-1}\left(\frac{\sqrt{\frac{m}{M}}}{\xi_{sc} + \xi_{lv}}\right)$$



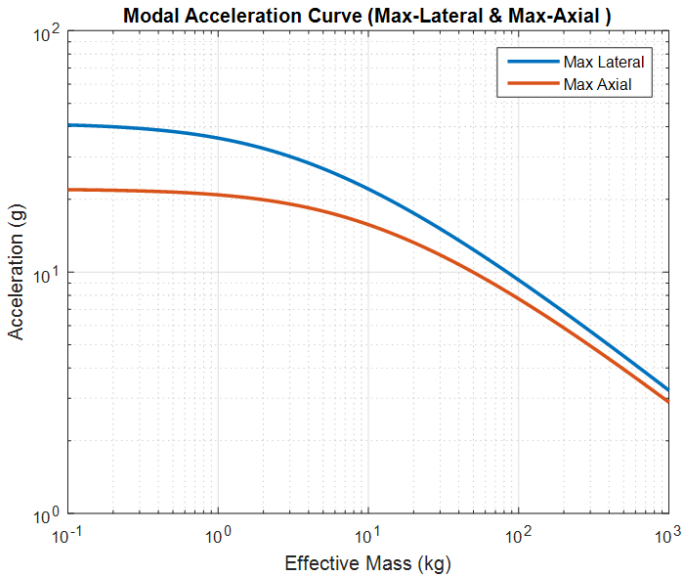


Analysis Input - Background (3/3)

Modal MAC Loads Analysis vs. Sine Vibe Analysis

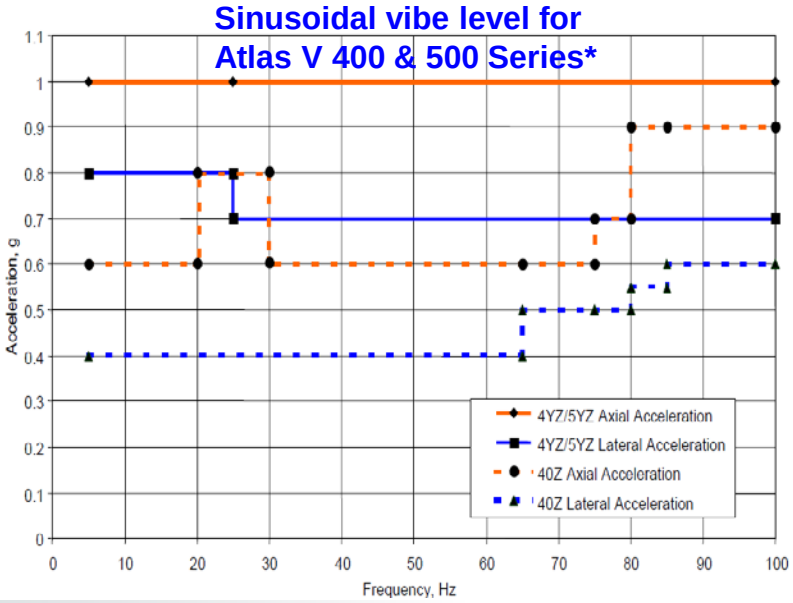
Modal MAC Analysis Inputs

- *FEM of Payload*
  - modes, frequencies, effective masses, etc.
- *Modal Mass Acceleration Curve*
- *Payload to Launch Vehicle Interface Accelerations*



Sine Vibe Analysis Inputs

- *FEM of Payload*
  Base drive frequency response
- *Quasi-sinusoidal vibration level*
- *Quasi-static load factors*



*** Atlas® launch system mission planer's guide**

Modal MAC Bound

- Absolute acceleration

$$\ddot{x}(t) = \begin{bmatrix} \phi^{cm} & \phi^{nm} \end{bmatrix} \begin{Bmatrix} \ddot{x}_r \\ \ddot{q}_s \end{Bmatrix} = \sum_{r=1}^{i} \phi_r^{cm} \ddot{x}_r(t) + \sum_{s=1}^{N} \phi_s^{nm} \ddot{q}_s(t)$$

$$\leq \sum_{r=1}^{i} \left| \phi_r^{cm} \ddot{x}_r^{mean} \right| +$$

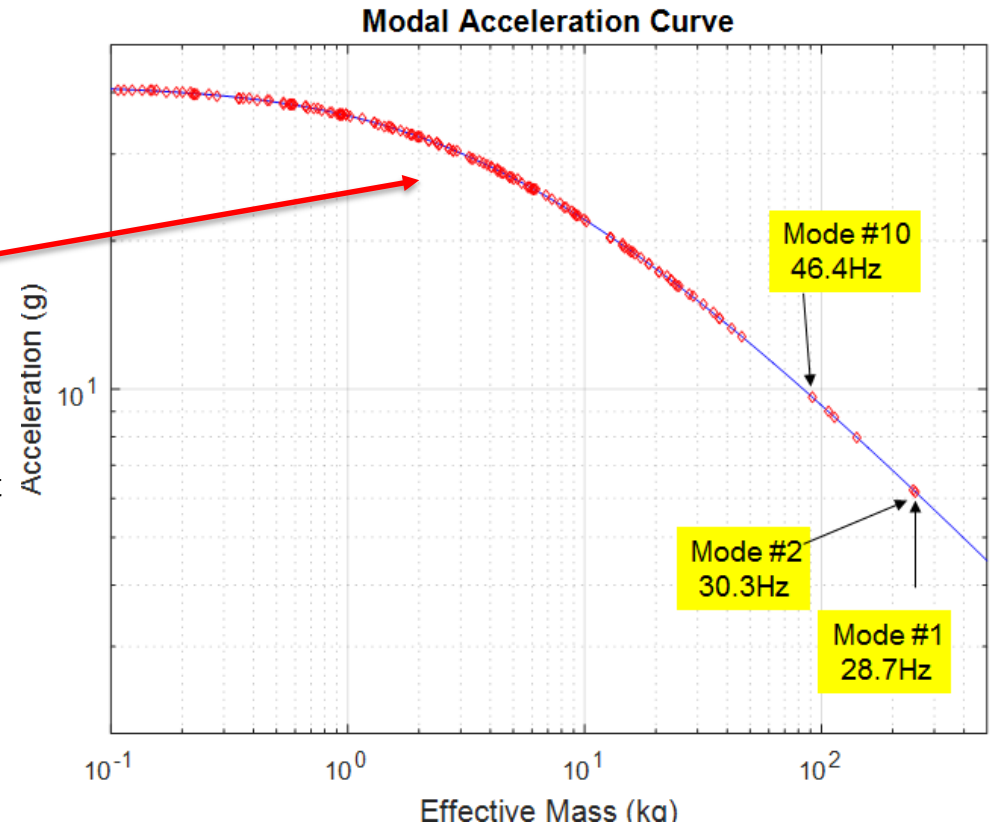
$$\sqrt{\sum_{r=1}^{i} \left(\phi_r^{cm} \ddot{x}_r^{dyn} \right)^2 + \sum_{s=1}^{N} \left(\phi_s^{nm} \sqrt{m_s^{eff}} \boxed{\ddot{q}_s^{MMAC}} \right)^2}$$

$\ddot{x}_r^{mean} =$ P/L to L/V interface accel, mean component

$\ddot{x}_r^{dyn} =$ P/L to L/V interface accel, dynamic component

$\sqrt{m_s^{eff}} =$ Effective mass, square-rooted

$\ddot{q}_s^{MMAC} =$ Modal Mass Acceleration



- Root-Square-Sum *scale* eigenvectors with $\ddot{x}_r^{dyn}$
- Scale factor determined by MMA Curve and square-root effective mass

Concept of Effective Mass

- Effective mass for mode *s*

$$m_s^{eff} = \sum_{r=1}^{3} \left(\boldsymbol{\varphi}_s^{nm}\right)^T \mathbf{M} \cdot \boldsymbol{\varphi}_r^{RB}$$

$\boldsymbol{\varphi}_s^{nm} =$ normal mode *s*

$\mathbf{M} =$ Mass matrix

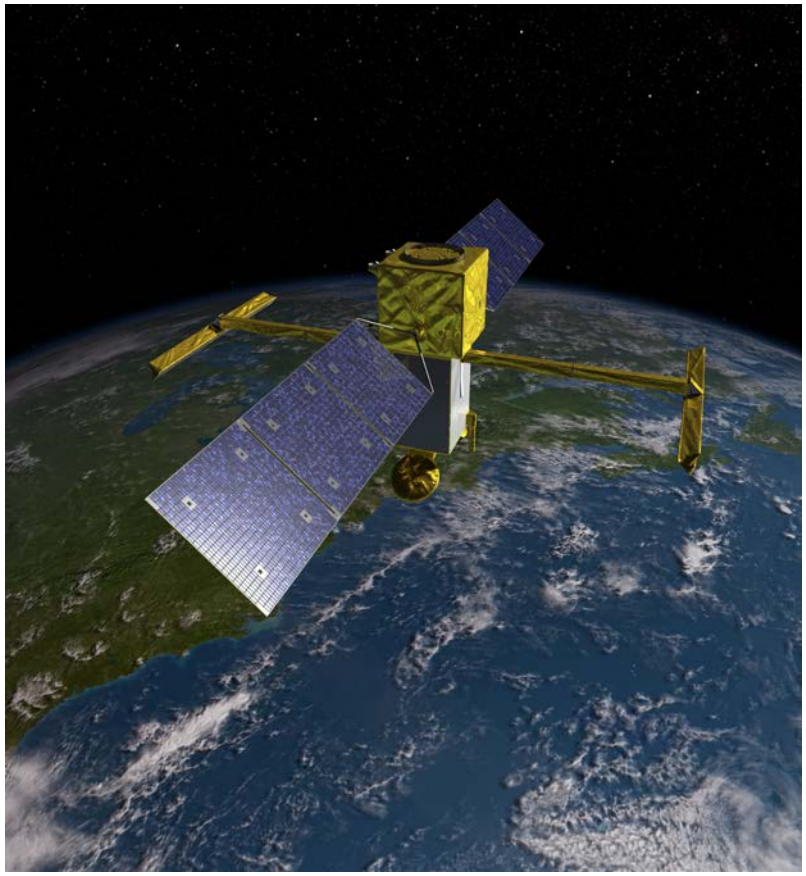
$\boldsymbol{\varphi}_r^{RB} =$ Rigid body mode, direction *r*

- NASTRAN case control command *MEFFMASS* turn on calculation
- Equivalent physical mass of the corresponding modal DOF
  - *summation over all modal effective masses will result in rigid-body mass*
  - *measure sufficiency of mode numbers*
- a measure to gauge significance of a vibration mode
  - Modes with low effective mass yield low responses by enforced acceleration
  - Modes with high effective mass can be readily excited by base excitation

– *Proportional to the reactions force acting on the base of the base drive enforced acceleration*

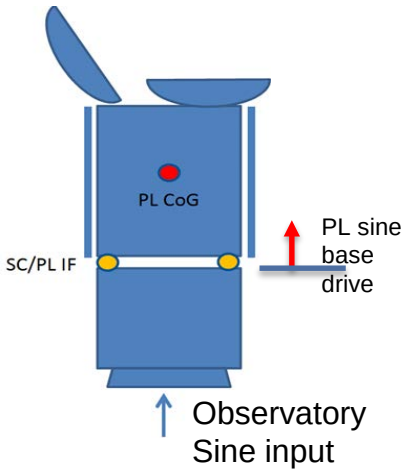
Surface Water Ocean Topography (SWOT) Mission

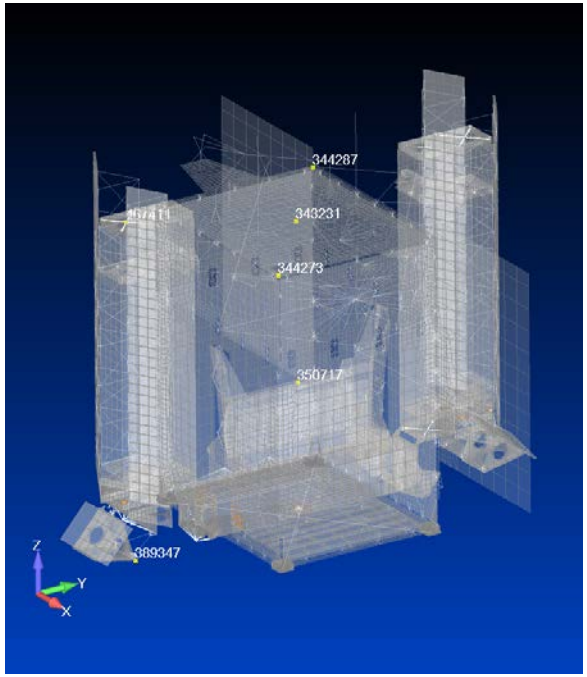
- **Mission Objective**: provide global survey of Earth's oceans and terrestrial surface waters
  - *combine the concepts of WaTER (Water and Terrestrial Elevation Recovery) and the Hydrosphere Mapper*
- Collaboration between NASA and French CNES
- Candidate Launch Vehicles
  - *ATLAS V*
  - *FALCON 9*



SWOT Overall Sine Notching Strategy

- SWOT Payload mass comparable to S/C bus mass: P/L and S/C bus modal behaviors coupled
- Perform extensive Observatory Model sensitivity studies on stiffness/mass variation of S/C and P/L
- Identify several acceleration outputs as representative global P/L responses
- Envelope acceleration of all sensitivity results for each acceleration output
- Force Limiting
  - *Sine inputs notched so that P/L to S/C interface load, not exceeding quasi-static load*
- Response Limiting
  - *Sine inputs notched so that strategically selected P/L responses do not exceed Observatory-level sine responses.*

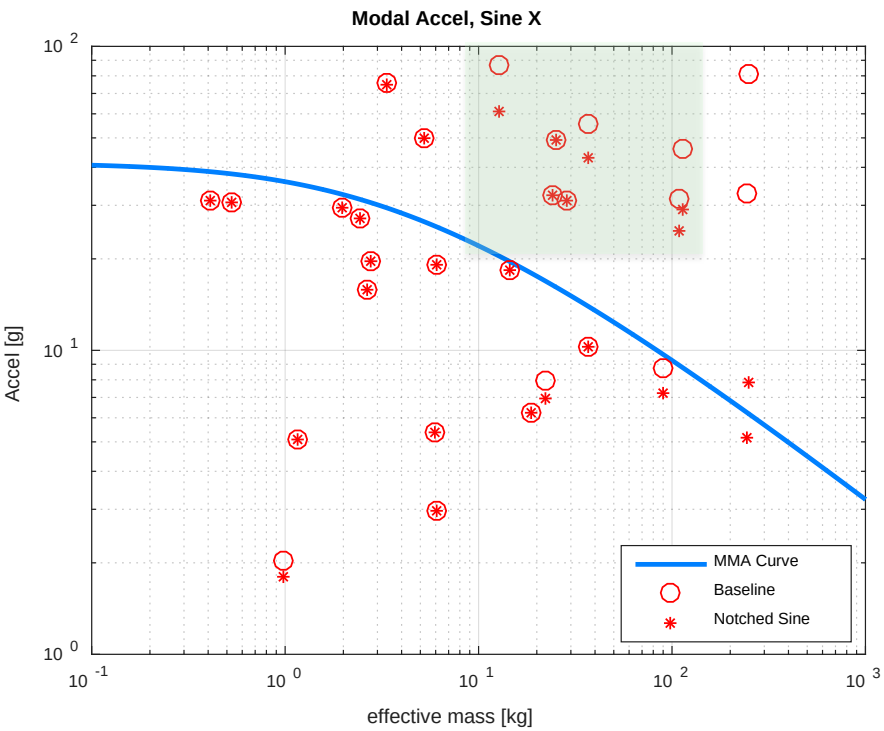


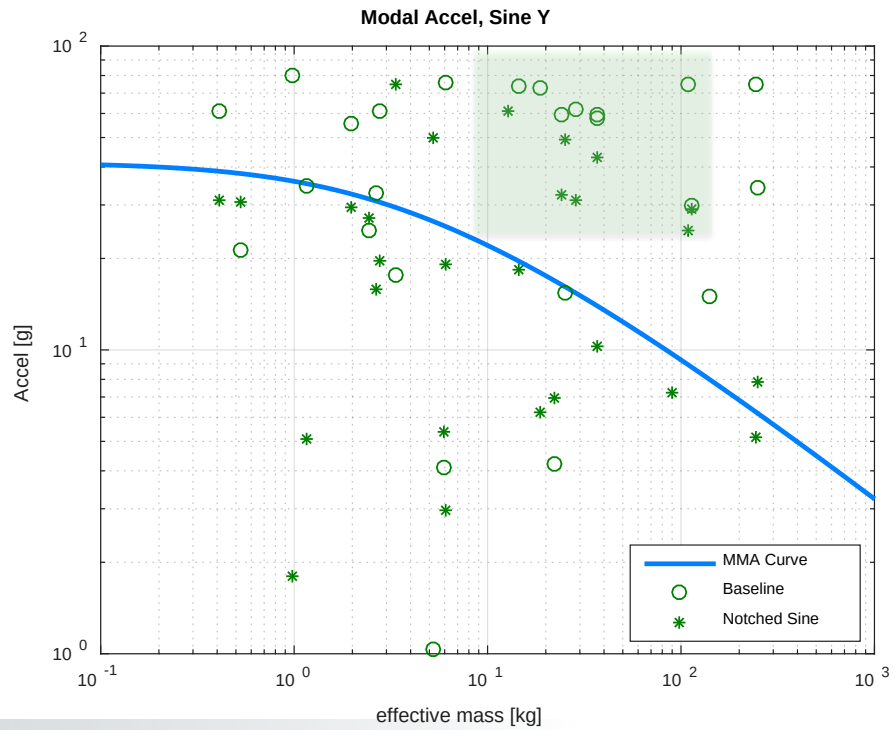


Notched Modes in Modal Acceleration Curves

Force Limited Sine Vibe Analysis

- Notched input sine vibe level bring down the major bending modes (#1, #2)
- Modes of large effective mass (10^1 ~ 10^2 kg) still well above MMA Curve

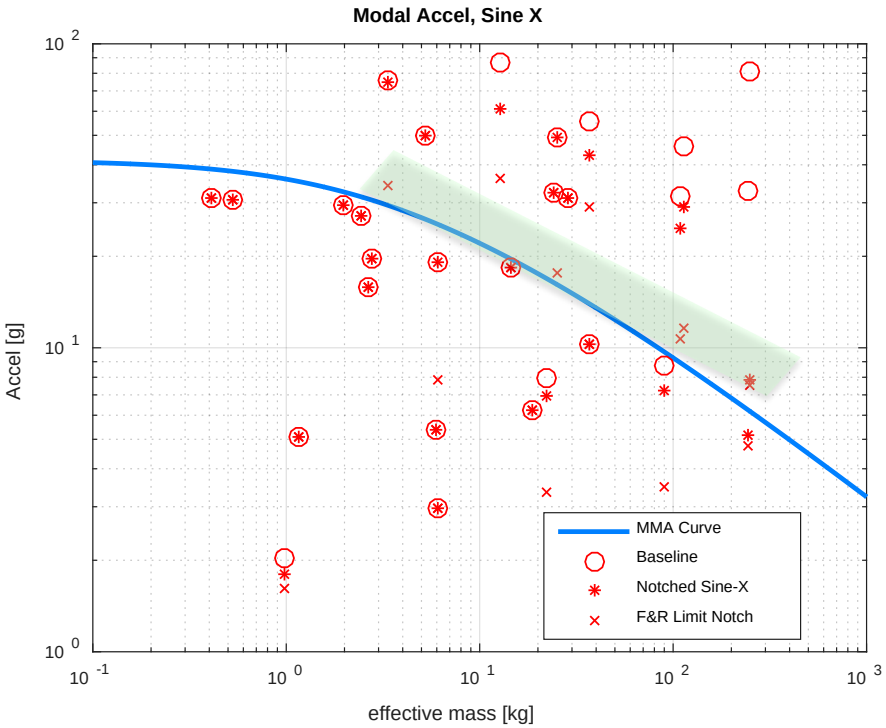


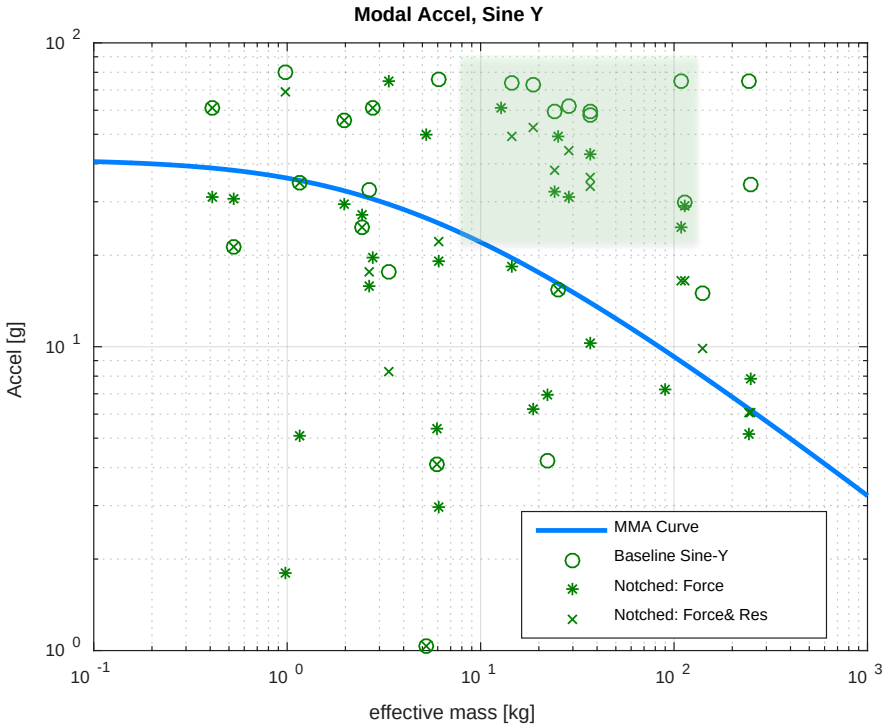


Notched Modes in Modal Acceleration Curves (2)

Force and Response Limited Sine Vibe Analysis

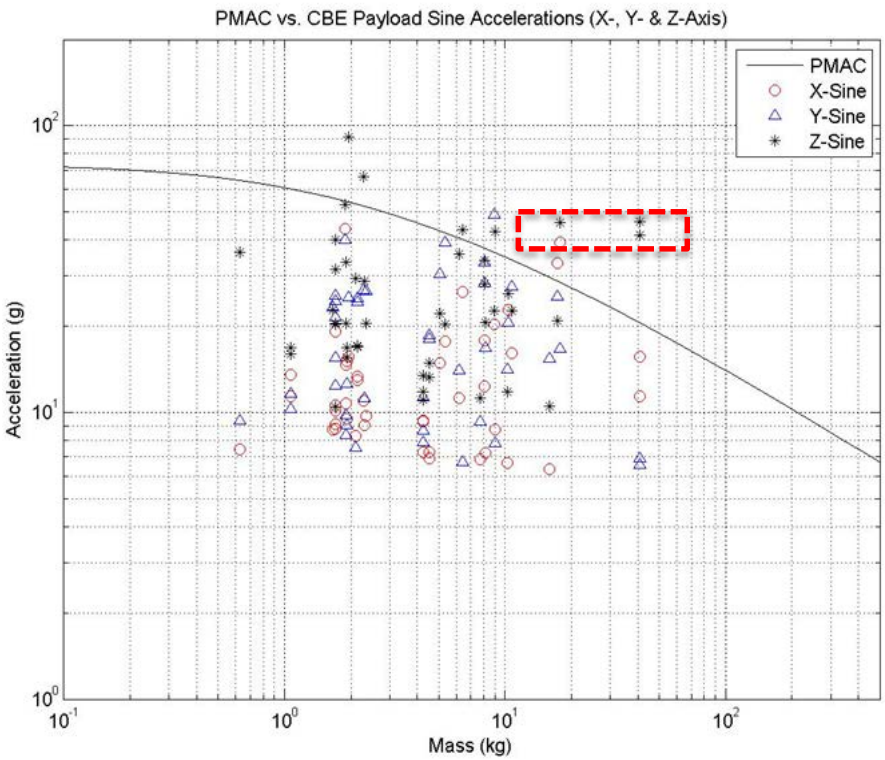
- As a result of notched sine input level due to force and response limiting modal acceleration responses move lower and closer to MMA Curve
  - Most Sine-X modes response in the vicinity of MMA Curve
  - Sine-Y Modes of large effective mass (10^1 ~ 10^2 kg) still well above MMA Curve

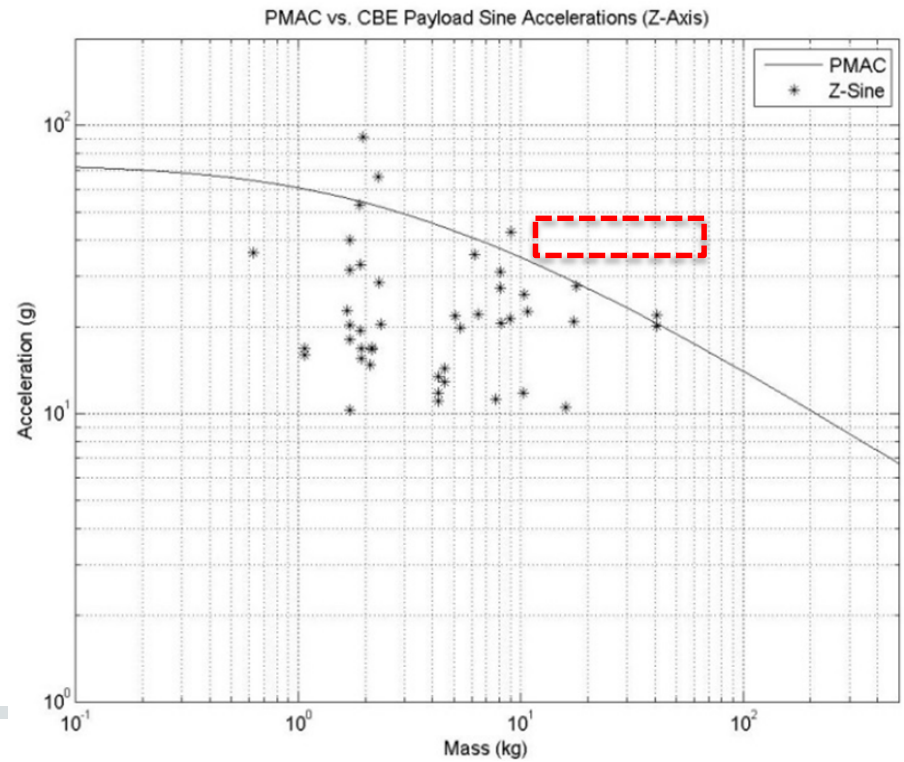




Payload Sine Result vs. Physical Mass Acceleration Curve

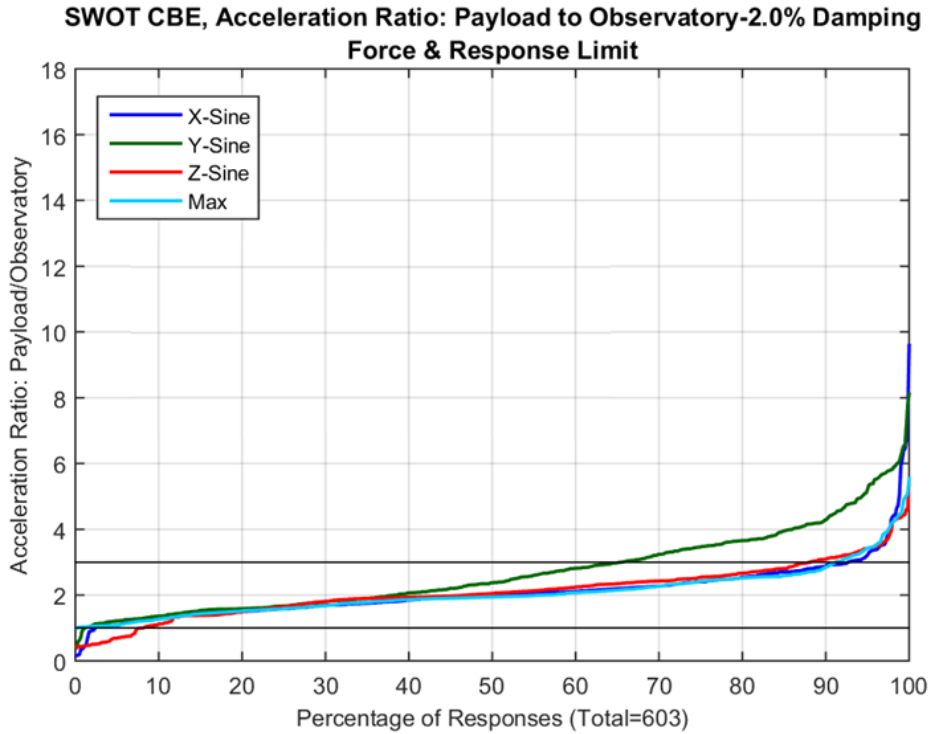
- Mass Acceleration Curve exceedances of maximum sine responses are mainly driven by z-axis sine.
- Activating response limiting for the z-axis sine reduce Mass Acceleration Curve exceedances





SWOT Sine Vibe Analysis Results

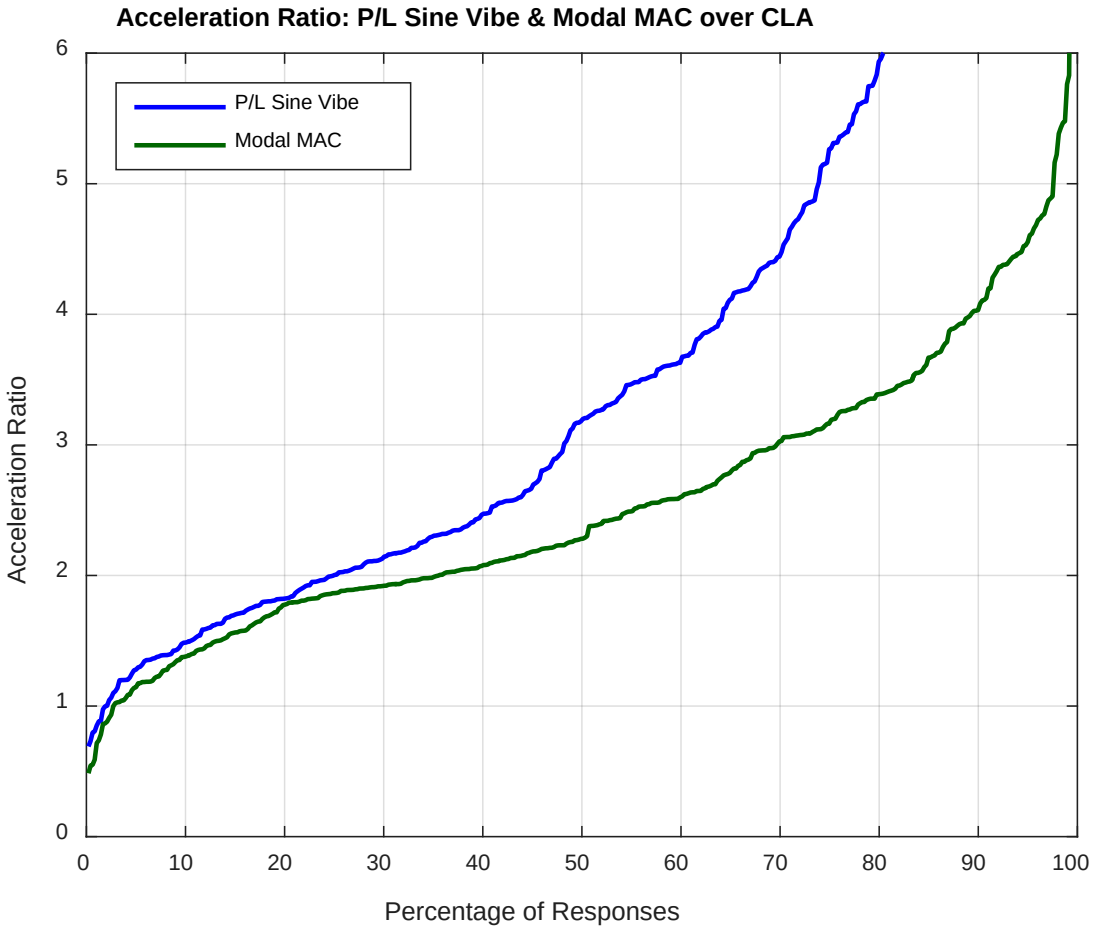
Acceleration Ratio: Payload / Observatory



- Acceleration from notched P/L sine-x and sine-y analysis bound those from Observatory
  - *Sine-Y accelerations show more conservatism over Sine-X due to more modal responses exceedance over MMA Curve*

SWOT Sine Vibe & Modal MAC Analysis Results

Acceleration Ratio –Sine Vibe & Modal MAC over Couple Load Analysis



Summary

MMAC vs. Base Drive Sine Vibe

- Mapping the modal acceleration responses from base drive sine vibration analysis to the “acceleration vs. effective mass” space introduces another perspective on the sine vibration analysis
- Compare the sine vibe modal accelerations responses against Modal Mass Acceleration Curve to assess the input sine level
- In general, notching sine vibe input level based on force-limiting of quasi-static load interface load can bring down modal accelerations of the first bending modes closer to Mass Acceleration Curve
- It is an indication for additional notching on the input sine level when modal (or physical) accelerations of large effective mass register significant exceedance over Mass Acceleration Curve

Thank you

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